Germanium Crystals Measure both energy and position

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Germanium crystals have long been used to study photons with energies from 50 keV to 10 MeV. Their excellent energy resolution (approaching 0.1%) has created numerous applications in nuclear and particle physics, especially in studies of nuclear structure. Their major limitations are their poor position resolution and inability to reconstruct multiple interactions. Photons with energies less than a few MeV interact primarily by Compton scattering. They usually interact several times before stopping, and many photons escape from conventional detector arrays without depositing their full energy. These partially reconstructed events constitute a substantial background to measurements. To reduce this background, existing germanium detectors are usually surrounded by thick anticoincidence (veto) counters. This veto greatly reduces the efficiency of large detector arrays

Now, germanium crystals are being made to do double duty, measuring the interaction points as well as the deposited energy, allowing for full 3-dimensional reconstruction of the energy deposition. The crystals work like miniature time projection chambers, with the charge deposition at each point in the crystal measured. A central cathode embedded in the crystal generates a radial electric field. Electrons liberated by photon interactions in the crystals drift to segmented anodes which cover the crystal surface. Charge sharing between adjacent electrodes allows position resolutions of 1-2 mm, far better than the current 1-crystal (5-10 cm) resolution. The electron drift time is measured, giving the depth of the interaction in the crystal, providing 3-d space points. With good segmentation, complex interactions can be reconstructed, greatly increasing the photon detection efficiency while maintaining optimum resolution.

Even for simple events, the improved position resolution is extremely attractive. The resolution could lead to better images from Positron Emission Tomography cameras, where two reconstructed 511 keV photons are used to localize positron annihilation in patients for a variety of medical and biological applications.

In many experiments to study very unstable nuclei, excited nuclei are produced at high velocities. To obtain gamma ray spectra from these nuclei, it is necessary to correct the photon energies for the nuclear Doppler shift; the accuracy of this correction depends on the precision of the photon position measurement.

Another important application is precision nuclear spectroscopy, where the increased efficiency is needed to study multi-step decays. For example, highly spinning nuclei may emit 20 or more photons as they de-excite. The ability to detect many photons in a single event greatly increases the experimental sensitivity to these reactions; high efficiency is critical for obtaining the required high-coincidence spectra.

Two large collaborations are developing gamma ray tracking arrays using segmented crystals with appropriate readout. In the U.S., the LBNL-led GRETA/GRETINA collaboration is building a segmented triple-crystal prototype module. Each crystal is covered with 36 electrodes (see the figure). The readout electrodes are segmented longitudinally and transversely. Each channel is instrumented with a low-noise pre-amplifier and a fast (100 Megasamples per second) accurate (14-bit) analog-to-digital converter. The energy resolution is 1.9 keV for 1.33 MeV gamma rays, comparable to the best unsegmented detectors. GRETINA will be composed of 10 triple-crystal modules covering about 25% of 4-pi. It will travel from accelerator to accelerator, following the best physics. The follow-on to GRETINA, the 120 crystal GRETA detector will have full 4-pi coverage.

The proposed 180 crystal (6500 channels) European AGATA array is also for nuclear spectroscopy. It uses a technology similar to Gretina. These arrays will have figures of merit several orders of magnitude better than existing large arrays like Gammasphere and Eurogam.

A few smaller arrays are already operational. At the Michigan State University cyclotron, the SeGA array comprises 18 crystals, each with 32 segment readout. These crystals are slightly smaller, with a 5 keV energy resolution. The EXOGAM array, at GANIL has 64 crystals, each with 4 segments, to measure the depth of interaction. Similarly, the CERN MINIBALL has 40 crystals, with 6 segments. The proposed Canadian TIGRESS array at TRIUMF will comprise 64 8-segment crystals.

The technique may also be used to reduce backgrounds in double beta decay and dark matter searches. The U. S. Majorana collaboration proposes to build a 200-crystal germanium detector containing 500 kg of 86% enriched ^{76}Ge germanium to study these topics. Simulations indicate that the position resolution obtainable with segmentation can lead to a factor of 5-8 rejection in backgrounds.

Another advantage of this technique is that the photon polarization may be determined by studying the angles in double-Compton scattering events.

For further reading:
http://greta.lbl.gov/
http://www-gsi-vms.gsi.de/eb/html/agata.htm
http://majorana.pnl.gov/

Figure Caption:

The 36-fold segmented prototype of GRETA. The inset shows the segmentation of the surface anodes